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Assessment of Middle Ear Function during the Acoustic Reflex Using Laser-Doppler Vibrometry

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14. ABSTRACT (CONTINUED).

Using this approach, we are able to directly measure the time course and magnitude of engaging the MEMC on middle ear movement. Changes in ossicular chain motion during MEMC were thus observed as frequency-dependent increases or decreases in TM velocity. Preliminary results suggest a more nuanced, across-frequency potential for middle ear gain or attenuation during the acoustic reflex.

Summary

Background

Over the past several years, recommendations from the American Institute of Biological Sciences (AIBS) panel have been made to update and/or replace current military standards and regulations that intend to protect individuals exposed to high-level acoustic impulses from hearing injury. One method recently implemented by the Department of Defense for determining the risk of hearing injury from impulsive noise exposures is the Auditory Hazard Assessment Algorithm for Humans (AHAAH). The AHAAH is an electrical equivalence model of the human ear designed to reproduce sound transmission through the ear in order to predict potential hearing injury from a given sound exposure; however, several key assumptions involving the effects of middle-ear muscle contraction (MEMC) on sound transmission through the middle ear during the acoustic reflex have not been validated.

Purpose

The aim of the current project was to develop a means for testing and directly measuring the presence and magnitude of MEMC. In the current study, we used laser-Doppler vibrometry (LDV) to measure tympanic membrane (TM) motion in response to an acoustic reflex-eliciting impulse as a proxy for assessing ossicular chain motion in human participants. The objective of this study was to determine the effects of stimulus intensity and frequency on MEMC.

Methods

Participants sat in the exam chair and listened to acoustic stimuli consisting of pure tones of various levels and frequencies. The laser was mounted on a surgical microscope and focused on the TM near the umbo. A continuous probe tone of varying frequencies was delivered to the ear measured by the LDV transducer. An elicitor stimulus was delivered to the contralateral ear via an insert earphone. The stimulus parameters, such as level and frequency, for both the elicitor and probe tones were varied.

Conclusions

Changes in ossicular chain motion during MEMC were thus observed as frequency-dependent increases or decreases in TM velocity. Findings establish the effect of the MEMC on middle ear movements following high-intensity acoustic stimulation. Results also suggest a more nuanced, across-frequency potential for middle ear gain or attenuation during the acoustic reflex. Knowledge gained from this study indicates the need for updates to hearing health hazard assessments, and increases our understanding of the potential for hearing injury in individuals routinely exposed to high-level impulsive noises.

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Introduction

Repetitive exposure to high-level acoustic impulses, such as those from firearms, increases the risk for hearing loss. Over the past decade, several recommendations have been made to update and/or replace current military standards intended to protect individuals exposed to high-level acoustic impulses from hearing injury (Murphy & Kardous 2012, Price 2005a, Price 2005b, Price & Kalb 1991, Wightman et al 2010). Recently, a system acquisition standard (MIL-STD-1474E) was adopted by the Department of Defense that requires the U.S. Army to use the Auditory Hazard Assessment Algorithm for Humans (AHAAH) developed by the Army Research Laboratory Human Research Engineering Directorate (ARL-HRED). The AHAAH is an electrical equivalence model of the human ear designed to simulate sound transmission through the ear in order to predict risk of hearing injury from a given impulsive sound exposure (Kalb & Price 1987, Price 2007a, Price 2007b, Price 2011). It should be noted that the MIL-STD-1474E is not a medical standard used for assessing health hazards associated with impulsive noise exposure; however, a medical standard is still needed. While the AHAAH represents a substantial advancement toward using biomechanically-based models to predict auditory injury, the model was developed using physiological data from small animals (Kalb & Price 1987), and thus several key assumptions may not hold when adapted to predict auditory injury in humans. This report describes experimental methods developed in the Auditory Protection and Performance Division (APPD) at the U.S. Army Aeromedical Research Laboratory (USAARL), Fort Rucker, AL to investigate assumptions of the AHAAH relating to the response of the middle ear musculature to high level impulse noise.

One aspect of the AHAAH model that has been identified as needing further research is the model's treatment of the middle ear and its function during the acoustic reflex (Davis et al 2001, Wightman et al 2010). In humans, the acoustic reflex consists of a middle-ear muscle contraction (MEMC) of principally the stapedius muscle in response to high-level acoustic sounds (Feeney & Keefe 1999, Silman 2012); whereas the acoustic reflex activates both stapedius and tensor tympani MEMCs in many animals (Forbes & Sherrington 1914, Mukerji et al 2010). Sound transmission from the ear canal to the inner ear is transferred via the ossicular chain, which consist of three bones (i.e., the malleus, incus, and stapes) within the middle ear. In addition, there is one muscle that attaches to the neck of the stapes (i.e., the stapedius) and one muscle that attaches the neck of the malleus (i.e., the tensor tympani). These muscles are innervated by branches of the facial (CN VII) and trigeminal (CN V) nerves, respectively, which convey sensory and motor function to the face and mandible. Notably, neither muscle is innervated by the vestibulocochlear nerve (CN VIII), which is responsible for conveying information from the ears to the central nervous system (Mukerji et al 2010). Contraction of the stapedius muscle stiffens the ossicular chain at the point of the stapes, affecting sound transmission through the middle ear. The latency of these muscle contractions varies with the level of the sound stimulus, but varies between approximately 40-200ms (Ruth & Niswander 1979). The result of this MEMC is an increase in acoustic impedance, and a reduction of the energy transferred into the cochlea.

A recent report by a group of researchers (L-3 Applied Technologies, Inc., 10180 Barnes Canyon Rd., San Diego, CA 92121-5701) has updated several model parameters to better match responses measured in humans (Zagadou et al 2016); nevertheless, several important

assumptions in the AHAH model need to be validated. In particular, two assumptions regarding the effects of the MEMC on sound transmission have not been verified. First, the AHAH model posits that the MEMC during the acoustic reflex attenuates sounds entering the cochlea by up to 20 dB at all frequencies (Murphy et al 2010); however, the amount of attenuation afforded by the MEMC in humans is unclear and has not been validated. The second assumption is that the MEMC can be classically conditioned to engage prior to an acoustic impulse. The latency of the acoustic reflex is sufficiently long that the resulting MEMC would not affect (i.e., protect) sound transmission for an impulse noise exposure. The AHAH model assumes that “if the listener knows that the shot is going off, or if the impulse is one of a series (as in a machine gun), the muscles *might* be contracted at the time the impulse arrives” (Price 2010). Thus, the AHAH model allows the user to decide whether to evaluate the response to the impulse as though it were “unwarned” (onset of MEMC occurs sometime after the impulse due to the reflex latency) or “warned” (MEMC is engaged prior to the start of the impulse). It is unclear whether the MEMC can be elicited prior to the sound exposure (i.e., the “warned” response), and the amount of protection afforded in these “warned” situations has not been quantified. It is imperative that both of these assumptions be experimentally validated before accurate damage risk criteria can be established. In particular, either over-estimating the amount of attenuation provided by the MEMC (assumption one), or predicting a MEMC when none is present (assumption two), would both result in the model under-estimating the risk of auditory injury for a given exposure.

It was the aim of the current project to develop a means for testing and directly measuring the presence and magnitude of MEMC during both ‘warned’ and ‘unwarned’ acoustic exposures. The objective of this study was to determine the effects of stimulus intensity and frequency on MEMC, measured via tympanic membrane (TM) motion using a laser-Doppler vibrometry (LDV) system. Findings from this study provide essential information for the development of experimental procedures aimed at assessing the various states of the middle ear musculature to “warned” and “unwarned” acoustic impulses exposures.

Methods

The current study was conducted as a test (not research), after determination by the USAARL Regulatory Compliance Office. All of the adult subjects (n = 5) who volunteered to participate were members in the APPD at USAARL. As such, subjects did not sign an informed consent document; however, they were provided a test information sheet and told they could withdraw from the test at any time. Subjects underwent an otoscopic examination to ensure the ear canals were unoccluded and that the TM could be visualized. Acoustic reflex thresholds were obtained for each subject prior to testing in order to confirm that subjects had acoustic reflexes that could be elicited by standard audiometric test equipment.

Here we used LDV technology to carefully measure the MEMC elicited by a brief acoustic signal (hereafter referred to as the elicitor tone), presented to the ear contralateral to the LDV measurement ear. Changes in the velocity of the TM motion responding to a continuous lower level acoustic stimulus (hereafter referred to as the probe tone) presented to the ipsilateral ear (re: LDV measurement) were used to identify the MEMC effect. The stimulus parameters, such as level and frequency, for both the elicitor and probe tones were varied. Elicitor levels

were presented relative to individually measured acoustic reflex thresholds for each subject obtained using the Interacoustics Titan™ System. Data were analyzed across subjects.

Equipment

During testing, participants sat in an otolaryngology exam chair (Reliance® Model 980/981) with their head restrained in a sound attenuating booth located in the APPD laboratory. The laser-Doppler vibrometer (Polytec OFV-534) is a precision optical transducer used for measuring vibration velocity at a fixed point. The technology is based on the Doppler Effect, sensing the frequency shift of back scattered light from a moving surface. Briefly, LDV works by comparing the frequency of the outgoing light with the frequency of reflected light from the moving surface, where the frequency of the reflected light is modulated by the velocity of the reflecting object. Stimuli were presented to participants during LDV testing at levels relative to the reflex threshold measured by the Interacoustics Titan system. All acoustic stimuli during LDV testing were presented to the participants using Etymotic Research ER-3C earphones. Stimulus presentation and LDV data acquisition were performed using a Tucker-Davis Technology (TDT) system controlled by custom-written MATLAB® software.

Procedure

Participants sat in the exam chair and listened to acoustic stimuli consisting of pure tones of various levels and frequencies. A head strap was placed across the forehead (see Figure 1A) to secure the head to the chair. An insert earphone was placed into the left ear of the participant in order to deliver the acoustic reflex-eliciting stimulus. In the right ear, an aural speculum (covered

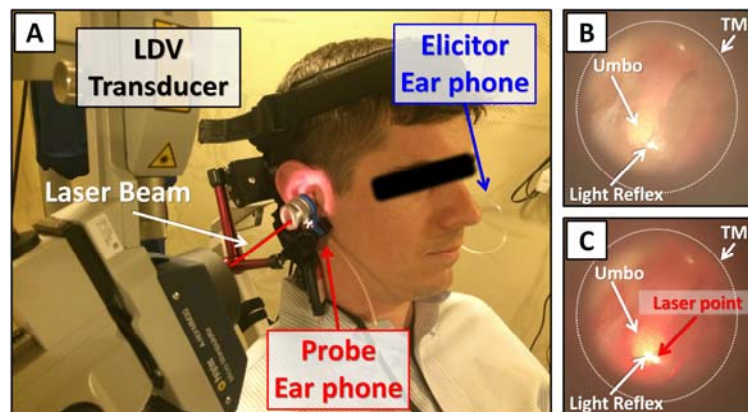


Figure 1. Experimental setup. A) The LDV was mounted on a surgical microscope and the laser beam was focused in the ear through an aural speculum. B) The light reflex of the tympanic membrane (TM) near the umbo. C) The laser point placed onto the light reflex.

with a glass window) was placed into the ear canal and fixed into position so that the participant's TM could be visualized. An earphone was attached to the speculum in order to deliver the probe stimulus. Using a surgical microscope (Zeiss POMI-1), the laser beam was focused on the light reflex near the umbo of the TM in the right ear (Figure 1B and 1C). The position near the umbo was chosen because the manubrium of the malleus is firmly attached to the TM at this point, is

located near the center of the TM, and represents a reliable anatomical landmark across individuals. In addition, this placement is near the point of maximum excursion along the manubrium of the malleus and is generally sufficiently reflective, thus providing a high signal-to-noise ratio signal (Beyea et al 2013, Rööslä et al 2012, Whittemore et al 2004).

In order to quantify the MEMC, we used LDV to measure tympanic membrane motion before and after elicitor tone presentation. The TM of the participant was set into motion with a probe tone in the same ear as the LDV measurement (red signal), and the MEMC was elicited by presenting the elicitor tone in the opposite (blue signal) ear via Etymotic Research ER-3C earphones (Figure 2). The probe tone was played continuously throughout testing, while the elicitor tone was 500 ms in duration, and presentations were separated by randomly assigned intervals of 10 ± 2 second. Note: the elicitor presentation occurs at a fixed probe stimulus phase for all repetitions of each condition in order to average across repetitions. The velocity of the TM in response to the probe stimulus was measured using the LDV system for single presentations of the elicitor, presented 5 times. The intensity and frequency of the elicitor and probe stimuli were varied in order to determine the optimal stimulus parameters for measuring MEMC during the acoustic reflex. The subject listened to approximately ~90-100 total elicitor presentations.

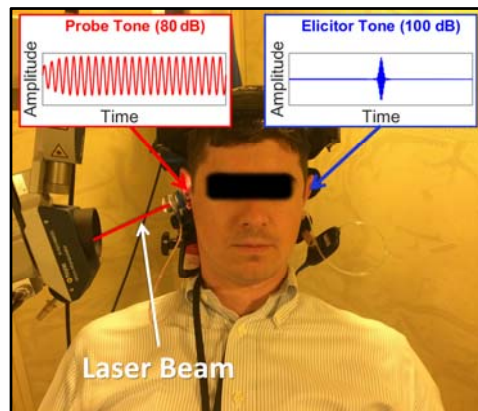


Figure 2. Visualization of stimulus presentation and experimental paradigm. A continuous probe tone was presented to the ear being measured by the LDV system. The elicitor was presented to the opposite ear in order to elicit a contralateral acoustic reflex

Data Analysis

The LDV recordings were band passed filtered using a 2nd order Butterworth filter with cutoff frequencies at $1/6^{\text{th}}$ octaves above and below the probe tone frequency. The median of all LDV recordings (usually five) made for each particular stimulus condition was calculated to reduce the contribution of large spikes in the LDV signal inherent to unavoidable motion of the subjects. The root-mean-square (RMS) velocity was calculated for two 500 ms time windows, one prior to the elicitor (i.e., the baseline) and one 100 ms following the elicitor presentation. The difference between these values was converted into a change from baseline (in dB). The engagement of the MEMC during the acoustic reflex can be seen in the LDV signal as a change in the TM's motion (in response to the probe tone) following the presentation of the elicitor.

Results

The motion of the TM (in response to the probe tone) during the elicitor presentation was compared to the TM motion immediately prior to the elicitor onset. Figure 3 plots the two acoustic signals (red and blue traces) and the median of the LDV signal (green trace) recorded during five presentations of the elicitor obtained from one subject. For the stimulus condition shown in Figure 3 (probe: 500 Hz at 90 dB; elicitor: 1000 Hz at 100 dB), the MEMC is observed as a decrease in the LDV recorded signal that begins at ~60 ms after the elicitor presentation. Note that in Figure 3 the ordinate of the LDV recording has been adjusted to highlight the signal decrease and does not show the full scale of the LDV signal. For ease of presentation in subsequent figures, the envelope of the median LDV signal (Figure 3C, black trace) was extracted using the Hilbert transform and then normalized to the average of the signal in the 500 ms window prior to elicitor presentation. Below, we report the effects of elicitor level, probe level, and probe frequency on the change in TM velocity during MEMC activation.

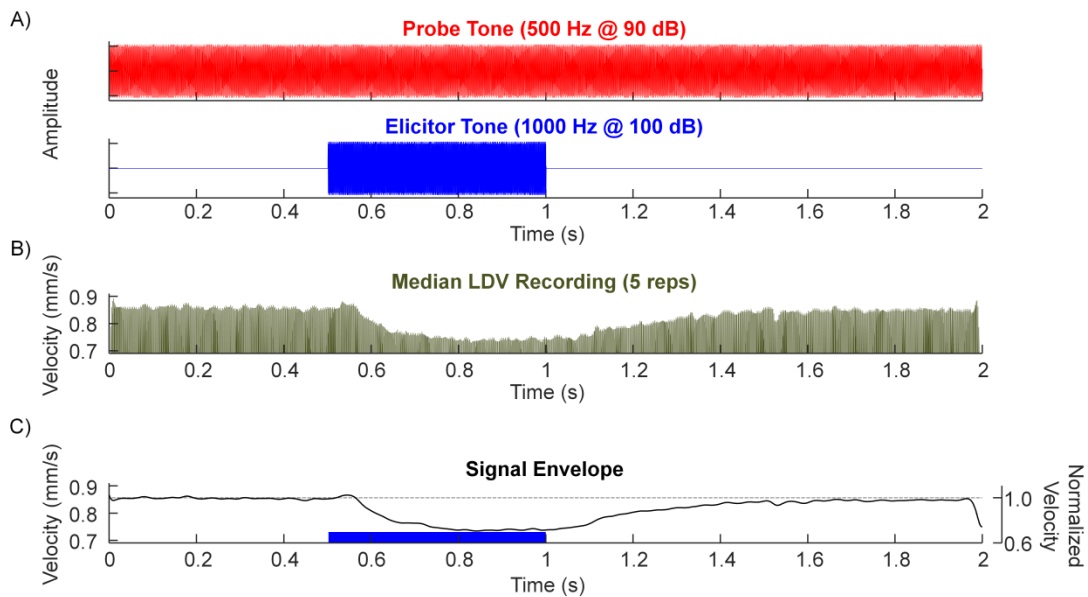


Figure 3. Stimulus paradigm and data analysis. A) The probe tone (red) and elicitor (blue) presented to the subject. B) The median filtered LDV recording (green) of 5 elicitor presentations. C) The envelope of the median LDV signal. The grey dashed line indicates the average of the signal (500 ms) window prior to elicitor presentation and the blue bar indicates timing of the elicitor tone presentation.

Elicitor Stimulus Level Effects

The level of the elicitor stimulus was chosen based on the acoustic reflex thresholds measured using an Interacoustics Titan™ System. Figure 4 shows the normalized TM velocity envelopes (as shown in Figure 3C) in response to a 500 Hz, 80 dB SPL (sound pressure level) probe, during presentations of a 1 kHz elicitor (onset at 1s) at three stimulus levels relative to the threshold obtained from the Titan™. The signal is variable and the MEMC is not visible when presented 10 dB below threshold. Presentation of the elicitor at or above the subject's acoustic

threshold level resulted in less variability, and a decrease in the velocity envelope between 1-1.5 s indicative of the MEMC activation. In addition, increasing the elicitor level increased the magnitude of response to the MEMC. This increase in MEMC magnitude may begin to asymptote above ~100 dB SPL (the maximum levels presented in this study) but across-subject variability obscured this result (Figure 5). Since the goal of this study was to demonstrate the ability to measure the MEMC using the LDV system, there was no plan to stimulate at sound levels above 110 dB, to avoid unsafe noise exposures.

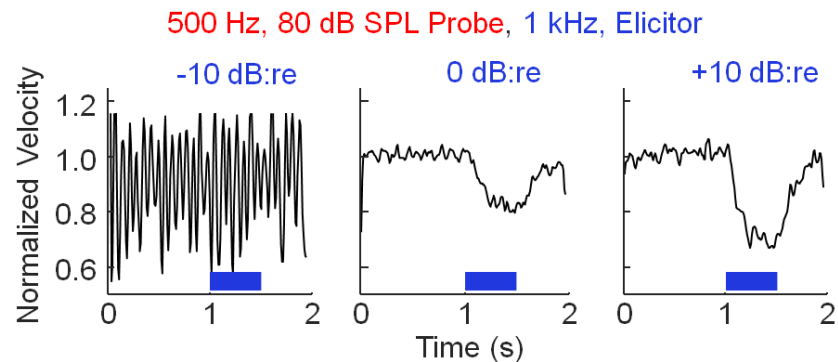


Figure 4. Elicitor level presentation relative to acoustic reflex threshold. Data collected from one subject at levels relative to reflex thresholds obtained with the Titan™ system. The blue bar in each plot indicates presentation of the elicitor.

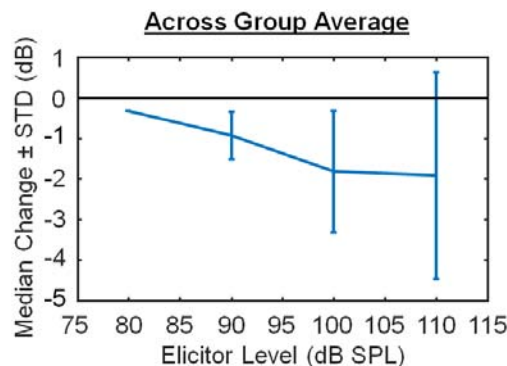


Figure 5. Summary of elicitor stimulus level effects. The across group average change in TM motion during the MEMC (in dB re: baseline) as a function of elicitor level (in dB SPL).

Probe Stimulus Level Effects

The presentation level of the probe stimulus primarily affects the quality of the recorded LDV signal. Specifically, increasing the probe level increased the signal-to-noise ratio (Figure 6), but did not change the magnitude of response MEMC for sound levels near and below the acoustic threshold (Figure 7). These data demonstrate that the MEMC can be reliably detected using probe stimulus levels that are below clinically measured acoustic reflex thresholds. As a result, the change in velocity observed at the TM during a MEMC can be attributed solely to the acoustic reflex eliciting stimulus with little to no contribution of the probe stimulus. This result

may not hold for higher stimulus levels, as the probe stimulus may directly elicit the acoustic reflex if presented above the reflex threshold level.

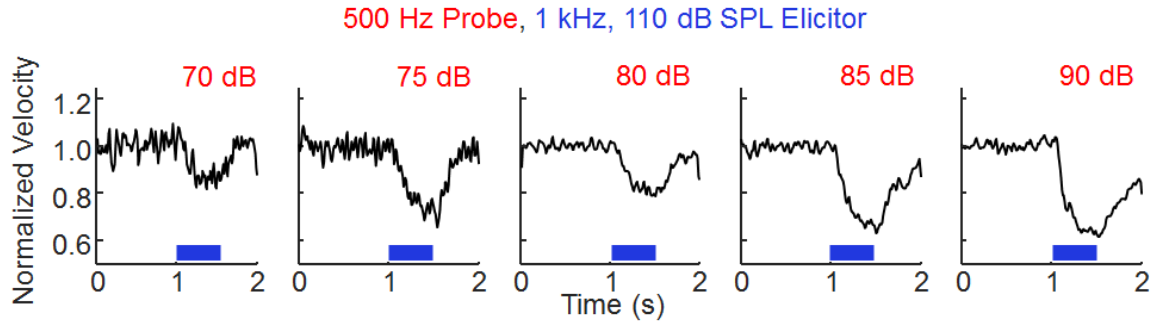


Figure 6. Presentation level effects of the probe stimulus. Data collected from one subject. The blue bar in each plot indicates presentation of the elicitor.

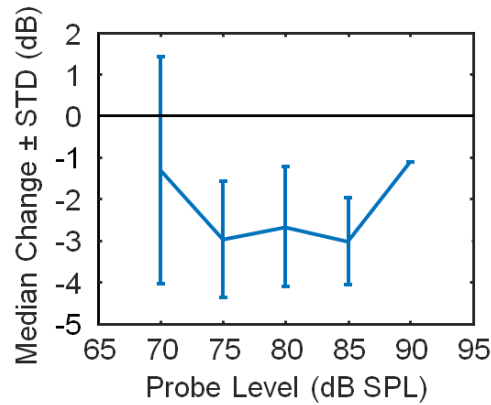


Figure 7. Summary of probe stimulus level effects. The across group average change in TM motion during the acoustic reflex for increasing probe levels.

Probe Stimulus Frequency Effects

The magnitude and direction of velocity change in TM motion varied as a function of frequency (Figure 8). In general, the MEMC decreased TM velocity for probe frequencies below 1 kHz, and increased TM velocities for probe frequencies at or above 1 kHz. The decrease in velocity was largest for a 500 Hz probe tone, which showed an average decrease on the order of ~ 4 dB and reached a plateau ~ 200 ms after elicitor onset. In contrast, the increase in velocity was largest in response to a 1.5 kHz probe tone, which increased on average by ~ 2 dB within a similar timeframe (~ 200 ms). The decrease in TM velocity was more variable and less reliable in response to a 226 Hz probe tone, and the increase in TM velocity decreased with increasing frequency such that no change from baseline is visible at 4 kHz.

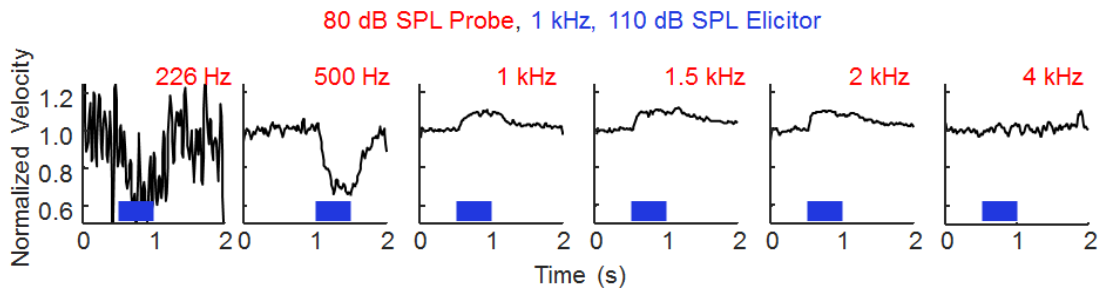


Figure 8. Effects of varying probe stimulus frequency. Data collected from one subject. The blue bar in each plot indicates presentation of the elicitor. Note the increase in the velocity following elicitor presentation for the 1, 1.5, and 2 kHz frequencies.

Discussion

The goal of the current technical report is to describe a method developed to measure middle-ear muscle contractions (MEMCs) elicited by the acoustic reflex using a laser-Doppler vibrometry (LDV) system. Similar methods and findings have been reported previously (Svane-Knudsen & Michelsen 1989); however, the present study directly measured the time course and magnitude of the effects of a MEMC on TM motion. The data presented in this report provide guidelines for the stimulus parameters required to effectively measure the effect of an MEMC elicited by contralateral acoustic stimulation on TM motion.

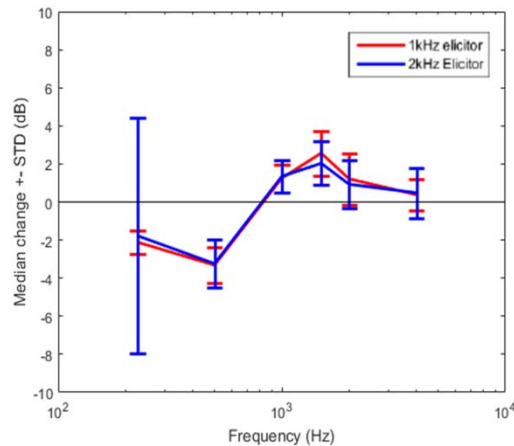


Figure 9. Summary of frequency-dependent effects on the middle ear muscle contraction. The across subject average change in TM motion as a function of probe frequency. The red and blue lines represent responses to a 1 and 2 kHz elicitor, respectively.

The magnitude of the MEMC response increases as the elicitor presentation level increases, whereas the presentation level of the probe stimulus mostly affects the quality of the LDV recorded signal. For the elicitor stimulus, the effect of the MEMC on the motion of the TM driven by low frequency (<1 kHz) probe tones was representative of the clinically measured acoustic reflex thresholds for the small number of subjects tested here ($n=5$). This indicates that,

elicitor presentations at levels similar to those typically used in clinical assessments of acoustic reflex thresholds (~85-90 dB, usually a 226 Hz probe tone) are appropriate for studies that involve observing the presence of a MEMC using a LDV system.

Across all the subjects tested, a decrease in the change relative to baseline was observed as the probe frequency increased (Figure 9). No differences in magnitudes were observed across elicitor frequencies (1 kHz vs 2 kHz). The increase in TM motion above 1000 Hz (see Figure 8) suggests the acoustic reflex may not necessarily be protective across the frequency spectrum. Similar findings regarding the frequency-dependency of middle ear movements during the acoustic reflex have been reported previously for both LDV and impedance measurements (Feeney & Keefe 1999, Svane-Knudsen & Michelsen 1989). In addition, the magnitude of change to middle ear vibrations during the MEMC measured here were comparable to the previous LDV measurements (Svane-Knudsen & Michelsen 1989), and to the change in absorbed power calculated from impedance measurements (Feeney & Keefe 1999). In both of those studies, the acoustic reflex resulted in a reduction of approximately 5 dB or less for frequencies below 1 kHz and increase of approximately 3-4 dB or less for frequencies up to 2 kHz. For frequencies above 2 kHz, there is little or no effect of the MEMC on middle ear movement. The findings presented here lend additional support to previous literature that the acoustic reflex may not be protective across the frequency spectrum.

Future research in the APPD at USAARL will utilize LDV and the methods reported to test the ‘warned’ response assumption of the AHAH, and determine whether the MEMC can be classically conditioned to engage prior to an acoustic impulse. Previous reports in the literature have been conflicting with some studies demonstrating classical conditioning of the acoustic reflex (Djupestrand 1965, Marshall et al 1975, Yonovitz 1976), while other studies were unable to observe the ability to contract the middle ear muscles in anticipation of loud acoustic impulses (Bates et al 1970, Brasher et al 1969). Using the techniques described here, we will thoroughly investigate the middle ear’s response to impulsive noise. This enables the capability to directly measure middle ear function during the MEMC for both the ‘unwarned’ and (potentially) ‘warned’ response. In the event that this future work shows that the MEMC can be classically conditioned, the methods reported here will also provide the ability to determine whether there is a difference in the morphology of the middle ear response (i.e., the magnitude and timing) for a ‘warned’ acoustic impulse presentation compared to an ‘unwarned’ condition. Such findings will help validate the amount of attenuation provided by the middle ear during the acoustic reflex for these two conditions, and would provide empirical evidence that could be used to better estimate the risk of auditory injury for a given impulse noise exposure.

Conclusions

To review, the goals of this project were to:

- 1) Develop techniques to measure MEMCs during the acoustic reflex using an LDV system.
- 2) Test the equipment setup and experimental design to be implemented in future studies investigating middle ear assumptions of the AHAH.
- 3) Evaluate various stimulus parameters and determine the optimal parameters required to measure middle ear function during the acoustic reflex with high fidelity.

In general, we demonstrated the ability to measure the MEMC in humans using LDV technology. The results reported here indicate a frequency-dependent effect of the probe stimulus, such that activation of the MEMC reduced TM motion for probe frequencies below 1000 Hz, and increased for probe frequencies above 1000 Hz. In addition, across all subjects we observed a decrease in absolute magnitude as probe frequency increased. Probe level mostly affects the quality of the LDV recorded signal, whereas the magnitude of the response increases as the elicitor level increases. No differences in magnitudes were observed across elicitor frequencies (1 kHz vs 2 kHz).

Recommendations

Any prospective work that plans to measure middle ear function based on these results and report in the future, should consider stimulus parameters. We recommend use of a probe stimulation level that is just below threshold to facilitate a good signal-to-noise ratio, while ensuring the probe stimulus itself does not activate or contribute to the MEMC during the LDV measurements. It is important to note that if the probe stimulation level is too low, the ability to observe the effect of the MEMC on TM motion will be severely limited.

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